CSU44001 – Analysis of Fuzzy Product - Coffee Roasting Machine

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1 Abstract

In this report we will provide an analysis of the fuzzy system found within a Coffee Roasting machine. This system or similar can be found within industrial grade coffee machines for autonomous control over factors that contribute to the roasting process of coffee. We will outline and examine the application of fuzzy logic and fuzzy controls to the scenario, detailing the model and rules. For the purpose of this report we used the following papers; Fuzzy Logic Applied at Industrial Roasters in the Temperature Control Based Fuzzy[1], Logic Temperature Control for a Coffee Roaster Machine[2].

2 Introduction

Coffee roasting is a process that is affected by many external factors, where the temperature for the duration of the roasting process is a key influencer in the quality of the resulting flavor. This process is used to transform the green coffee bean into the dark brown coffee bean most people are familiar with. Different levels of temperature create a different flavour profile associated with signature roasts which are often identified by colour. However, the roasting environment is not a stable one resulting in the time to temperature relationship not being a predictable one. The process is both time consuming and temperature sensitive, the temperature controller is essential to regulate this environment and crucial in creating a palatable taste.

3 Background

Coffee roasting is an age old tradition that can be traced back to the 15th century in the Ottoman Empire, where thin tin pans and spoons were used to darken the beans. In today's context, roasting is the second step in the industrial production of the coffee bean on a mass scale and is commonly used to describe the flavour profile. Coffee beans are both endothermic (meaning they absorb heat) and then at around 175 degrees celsius become exothermic (giving off heat). If bean heat themselves, temperature within a roaster must be adjusted. While beans are being heated they also release carbon dioxide and water (in the form of steam) as well as other natural compounds, these add to the moisture content of the roasting drum which can in turn affect temperature and the speed of roasting[3]. The roasting machine itself is a drum and hot air with the heat source usually being either natural gas, LPG, electricity, or even wood burning. The wood burning adds an additional dimension of flavour to the bean, however it is difficult to maintain a consistent level of heat which is why we chose to implement a fuzzy system for this case. The list below illustrates the ideal temperature of the roast, and the importance of temperature control.

Light Roast:

- **Very Light -** Cinnamon Roast - 196 degrees celsius
- **Light -**New England Roast - 205 degrees celsius

Medium Roast:

- **Medium -**City Roast - 219 degrees celsius

Dark Roast:

- **Dark -**Vienna Roast - 230 degrees celsius
- **Very Dark -** French Roast - 240 degrees celsius

The roasting machine drum, from our research across personal and industrial models, ranges from 1 to 120 kilograms, and ideally have a batch size of 70%. For simplicity, we chose to work with a drum with a maximum capacity of 60 kilograms, therefore having an ideal batch size of 42 kilograms[4]. For optimal bean development, there must be enough heat applied at the beginning of a roast. The beans are heated best when there is even coverage over the drum, and if a batch is large, the beans won't be exposed to the heat of the drum equally. If the beans take too long to heat up, then this results in a flat flavour - referred to as a 'baked' bean. On the other hand, the smaller the batch size, the quicker the beans will heat up. Combined with slower rotations of the drum, the more likely beans are to burn[5]. Although there are countless factors that could influence the roasting process, we focused on what we felt were key such as the Roast (dictated by temperature), Batch Size (the weight of the beans), Drum Speed (rotations per minute), and outputting the time (in minutes).

4 Model Description

4.1 Design

We are designing a fuzzy system that will control the drum speed, air temperature and batch size of a coffee roasting machine. Samples of the coffee bean aroma should be taken periodically by the coffee roasters until the desired scent is achieved. It is impossible to create a mechanism that will detect aroma and thus we must rely to some extent on human intervention. The input variables are batch size, the roast time (represented by a temperature) and drum speed. Other variables such as chamber pressure we assume to be a constant as result of ventilation within the machine. We chose to implement a Mamdani system over a Takagi-Sugeno, as we value precision over real-time computation. For this controller, our rules are implemented through membership functions for the antecedent (IF section of the rule) and consequences (THEN section of the rule). The Mamdani method is computationally expensive as it integrates a function that varies continuously, and for every rule an antecedent and consequent must exist[6].

4.2 Linguistic Variable - Fuzzification

Fuzzification is the process of converting non fuzzy variables into linguistic variables. The below section describes this process in the context of our system.

4.2.1 Input Variables

Batch Size: Our first input variable measures the weight of the raw coffee beans in the roasting chamber. The variables take the following linguistic terms; **low**, which defines all weights below 38 kg, **medium**, which defines all weights between 36 kg and 44 kg, and **heavy**, which defines all weights over 42 kg. There is overlap in the fuzzy sets **low** and **medium** for the range 36 kg < x < 38 kg and the fuzzy sets **medium** and **heavy** in the range 42 kg < x < 44 kg.

Temperature/Roast: Our second input variable measures the roast style of the coffee beans which is determined by the temperature. As described in the background section, different roast styles have ranges of temperature and the linguistic variables have been assigned to these ranges. Temperatures between 194 °C and 198 °C fall into **very light**, 203 °C and 207 °C into **light**, 217 °C and 222 °C into **medium**, 218 °C and 230 °C into **dark** and 228 °C and 234 °C into **very dark**.

Drum Speed: Our last input variables measures the drum speed in rotations per minute (RPM). The variables take the linguistic terms **slow**, **medium** and **fast**. The ranges are defined as follows, with x = rotation speed; any *x* less than 40 RPM is **slow**, any x between 38 RPM and 44 RPM is **medium** and any *x* is **fast** if it's greater than 42 RPM.

4.2.2 Input Variables

Time: The output variable of our system, time, is determined by the inference mechanism. The lowest possible time is 0 minutes but we define any time below 5 minutes as **very short**, thereafter any time between 4 minutes and 8 minutes is **short**, between 7 minutes and 11 minutes is **average**, between 10 minutes and 15 minutes is **above average** and lastly, any time after 15 minutes is **long**.

4.2.3 Relationship Between Variables

As evident in the fuzzy surfaces of the appendix (5.1, 5.2, 5.3) we identify distinct relationships between the values of the variables and their consequent effects on the output as well as the relationships they have between one another. In figure (5.1) the output time increases as drum speed decreases and roast temperature increases, thus creating an inverse relationship between these two variables.

In figure (5.2) drum speed and batch have a direct relationship with each other as each has an inverse relationship with time. As batch size and drum speed decrease, time will increase.

In figure (5.3) roast temperature has a direct relationship with time, with time increasing as roast temperature increases; conversely, time decreases as size batch size decreases. Therefore, roast temperature and batch size have an inverse relationship with time.

4.3 Base Rules - Inference

Inference is the process of making decisions using the fuzzy rules, which take the form of IF-THEN along with connectors AND and OR. Our base rules are included in the appendix. These rules we have formed replicate the scientific process behind coffee roasting. There is an inverse correlation between the rotational speed of the drum and the probability of the bean burning. In addition, there is an inverse correlation between the size of the batch and the overall roasting time.

4.4 Composition

Composition is an averaging procedure to compute the effective contribution of each of the rules to see the influence that each rule has given the fuzzy input values. For the composition we used the Min-Max method, where the value of the rule is taken with the minimum of the membership function and then they are combined using the maximum function to get the union of the fuzzy sets.

4.5 Defuzzification

Defuzzification is the process that takes the fuzzy set and represents it as a crisp number for the output. The function that are used in defuzzification are Maximum of Mean (MOM) and Center of Area (COA). We will be using Center of Area/Gravity or centroid method. This approach returns the value of the center of area under the curve by finding a vertical line which divides the continuous set into two.

5 Matlab Simulation

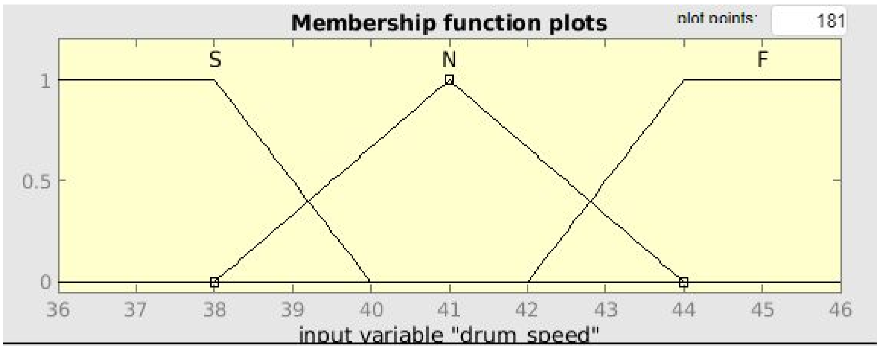


Figure 1

In the above figure we can note the behaviour of the variable which determines the drum speed of the coffee roasting mechanism. The universe of discourse of the variable varies from 38 RPM to 44 RPM. The pertinence symbols S, N and F represent slow, normal and fast, respectively.

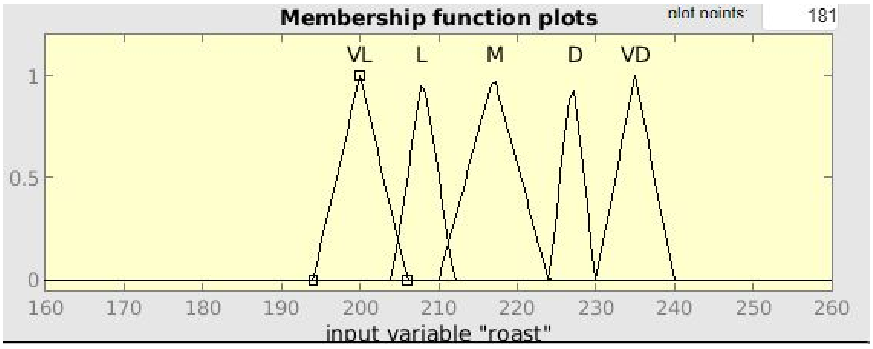


Figure 2

We can note in figure 2 the membership functions of the variable corresponding to roast or the temperature of the roasting chamber. The universe of discourse of the variable variance is from 175 °C to 260 °C. The pertinence symbol of the variables are VL (very light), L (light), M (medium), D (dark) and VD (very dark).

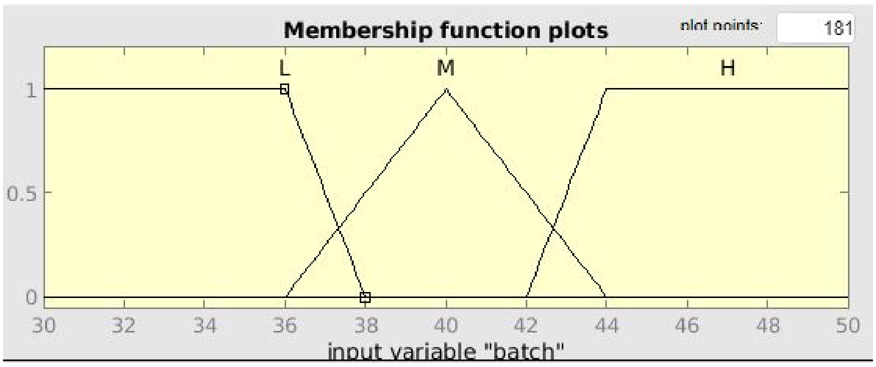


Figure 3

The above diagram shows the variable batch which is associated with the weight of the raw coffee beans in the roasting chamber. The universe of discourse for the variable variance is 36kg to 46 kg. The symbols of pertinence are L (light), M (medium) and H (heavy).

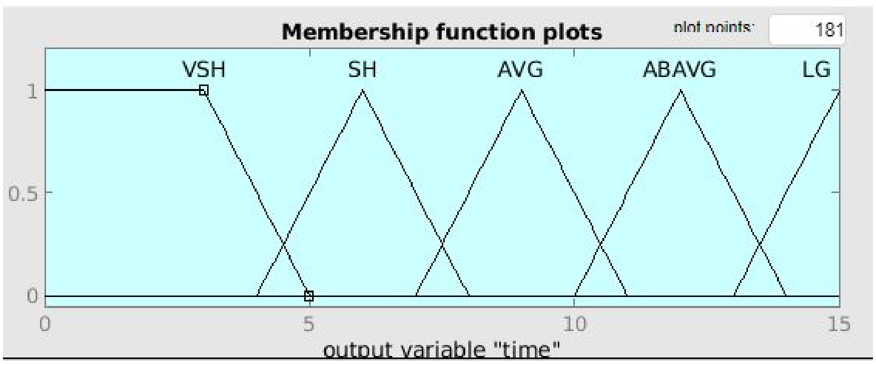


Figure 4

The diagram above describes the time output variable. The universe of discourse for the variable variance is 3 minutes to 15 minutes. The pertinence symbols are VSH (very short), SH (short), AVG (average), ABAVG (above average) and LG (long).

6 Results and Analysis

The following is an example simulation of our coffee roaster system:

Chad is the operator of our coffee roaster machine. He decides he wants to produce a Medium roast coffee using a low batch of coffee beans; the batch weighs 30kg. Chad sets the drum speed for the coffee roaster to be 43 RPM. He waits for the temperature of the fire to reach the ideal range for a medium roast which is 219 degrees celsius with a variance of 9 degrees below the optimal degree and 5 degrees above is acceptable. Using the following rules we created for our fuzzy system: IF Batch Size is *Light* AND Drum Speed is *Slow* OR *Normal* AND Roast is *Medium* THEN Time is *Short* and IF Batch Size is *Light* AND Drum Speed is *Fast* AND Roast is *Medium* THEN Time is *Average,* Chad gets the linguistic output values: Average and Short which when defuzzified gives him the time output of 11 minutes. Translating this result, it will take the system 11 mins to produce a medium roast on the coffee batch.

7 Evaluation

Our system tackles the variations that can occur during the coffee roasting process when using a mechanism that relies on fire as a heat source. It also covers the discrepancy in coffee weight and the rotations of the roasting drum with regards to their effect on the time of roasting. The system takes in these inputs at the beginning of the process and determines the time to be taken until they are finished roasting. The drum speed input is, arguably, a crisp input but we felt the need to include it as, according to the research conducted, the variation of the drum speed has a close relationship with the temperature and the weight of the coffee beans. Our initial variables also included pressure, airflow and water content but we felt these were not as relevant to the time and not linked as closely to the other variables. Initially, our intuition was to have quality as output however, this was very difficult to quantify as it is determined by experts based on the colour and aroma of the bean. Thus, we decided on time as the end output, which is useful for the operators of our system as it will prevent them from burning the beans due to miscalculations and errors.

8 Conclusion

It is evident that the process of roasting coffee beans is highly intricate. The resulting coffee taste and aroma have a direct correlation to the exact input variable values inputted into the system, in our case these variables being coffee batch size, temperature and drum speed. The process of choosing the input values is a blurry one as the line between the creation of different types of aromas is extremely fine; a slight increase in temperature can result in a completely different coffee taste and too slow of a drum speed can result in the coffee bean burning. The use of fuzzification is justified in our system as it allows us to deal with the uncertainty behind what input values correspond to the different coffee aromas.

9 References

[1] - Fuzzy Logic Applied at Industrial Roasters in the Temperature Control: https://www.sciencedirect.com/science/article/pii/S1474667015357165

[2] - Based Fuzzy Logic Temperature Control for a Coffee Roaster Machine: https://iopscience.iop.org/article/10.1088/1757-899X/434/1/012202

[3]- Discover the History of the Coffee Roaster https://www.perfectdailygrind.com/2019/09/discover-the-history-of-the-coffee-roaster/

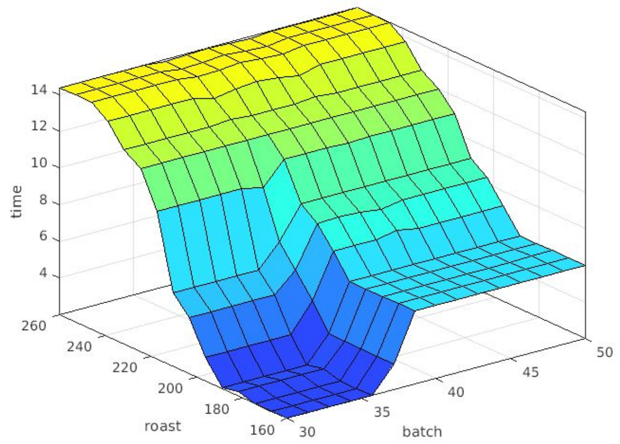
[4]- Understanding Drum Speed and its Affect on Your Coffee https://www.perfectdailygrind.com/2019/06/understanding-roaster-drum-speed-its-affect-on-your-coffee/

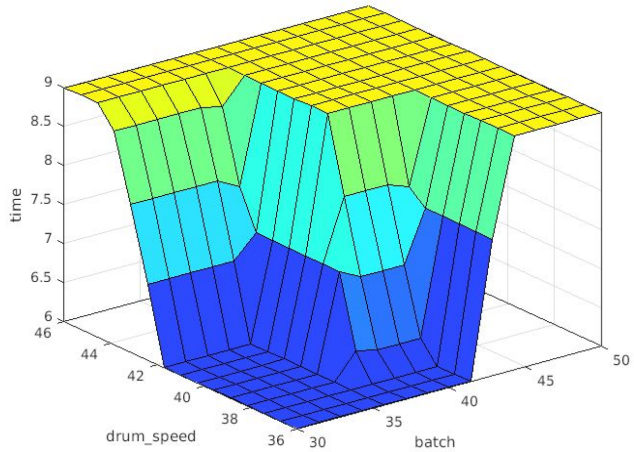
[5]- How Does Roaster Capacity and Batch Size Affect Your Coffee Roast https://www.perfectdailygrind.com/2019/09/how-do-roaster-capacity-batch-size-affect-your-coffee-roast/

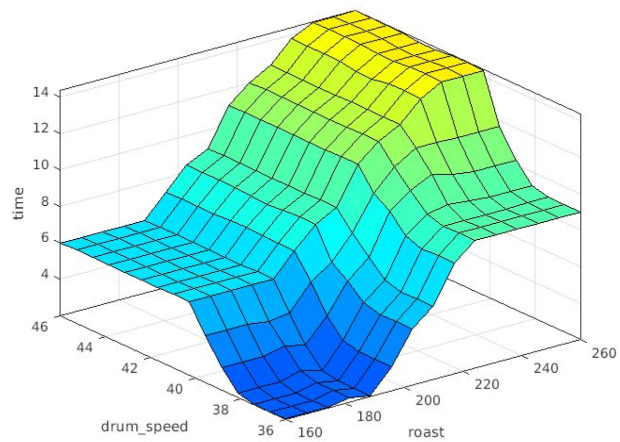
[6]- The Coffee Roasting Process using Fuzzy Mamdani: https://iopscience.iop.org/article/10.1088/1757-899X/407/1/0121

10 Appendix

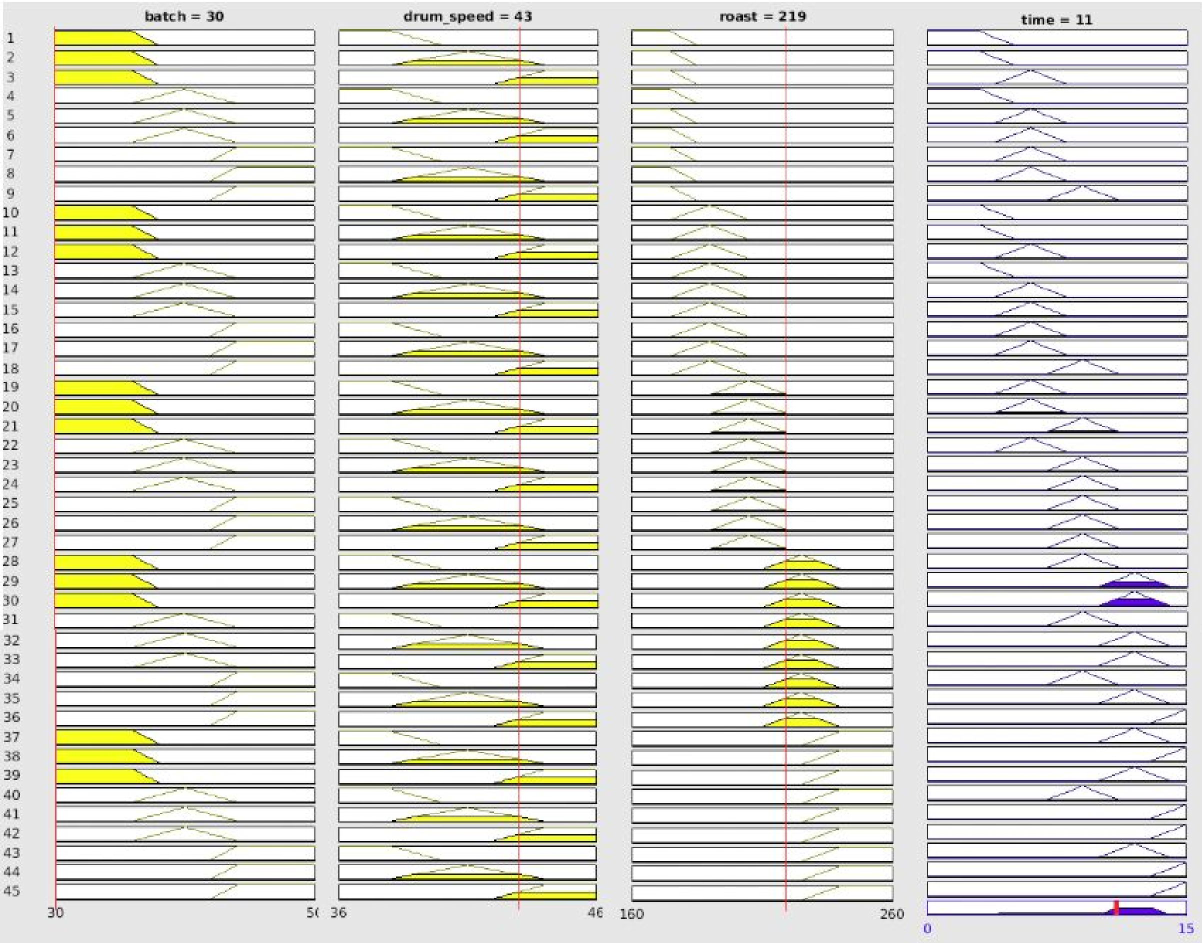
Fuzzy Surface Diagrams







Rules Diagrams



Fuzzification Table

Name	Semantic value	Domain
Input Variables		
Batch size	Low	x < 38 kg
	Medium	38kg < x < 44kg
	Heavy	x > 44 kg
Temperature/Roast	Very light	194 °C < x < 206 °C
	Light	204 °C < x < 212 °C
	Medium	210 °C < x < 224 °C
	Dark	224 °C < x < 230 °C
	Very Dark	230 °C < x < 240 °C
Drum Speed	Low	x < 40 RPM
	Normal	38 RPM < x < 44 RPM
	Fast	x > 42 RPM

Output Variables		
Time	Very Short	x < 5 min
	Short	4 min < x < 8 min
	Average	7 min < x < 11 min
	Above Average	10 min < x < 15 min
	Long	14 min < x

Rules

Very Light and Light Roast

- IF Batch Size is *Light* AND Drum Speed is *Slow* AND Roast is *Very Light* OR *Light* THEN Time is *Very Short*.
- IF Batch Size is *Light* AND Drum Speed is *Normal* AND Roast is *Very Light* OR *Light* THEN Time is *Very Short*
- IF Batch Size is *Light* AND Drum Speed is *Fast* AND Roast is *Very Light* OR *Light* THEN Time is *Short*
- IF Batch Size is *Medium* AND Drum Speed is *Slow* AND Roast is *Very Light* OR *Light* THEN Time is *Very Short*
- IF Batch Size is *Medium* AND Drum Speed is *Normal* AND Roast is *Very Light* OR *Light* THEN Time is *Short*
- IF Batch Size is *Medium* AND Drum Speed is *Fast* AND Roast is *Very Light* OR *Light* THEN Time is *Short*
- IF Batch Size is *Heavy* AND Drum Speed is *Slow* AND Roast is *Very Light* OR *Light* THEN Time is *Short*
- IF Batch Size is *Heavy* AND Drum Speed is *Normal* AND Roast is *Very Light* OR *Light* THEN Time is *Short*
- IF Batch Size is *Heavy* AND Drum Speed is *Fast* AND Roast is *Very Light* OR *Light* THEN Time is *Average*

Medium Roast

- IF Batch Size is *Light* AND Drum Speed is *Slow* OR *Normal* AND Roast is *Medium* THEN Time is *Short*
- IF Batch Size is *Ligh*t AND Drum Speed is *Fast* AND Roast is *Medium* THEN Time is *Average*
- IF Batch Size is *Medium* AND Drum Speed is *Slow* AND Roast is *Medium* THEN Time is *Short*.
- IF Batch Size is *Medium* AND Drum Speed is *Normal* OR *Fast* AND Roast is *Medium* THEN Time is *Average*
- IF Batch Size is *Heavy* AND Drum Speed is *Slow* OR *Normal* AND Roast is *Medium* THEN Time is *Average*
- IF Batch Size is *Heavy* AND Drum Speed is *Fast* AND Roast is *Medium* THEN Time is *Above Average*

Dark and Very Dark Roast

- IF Batch Size is *Light* AND Drum Speed is *Slow* AND Roast is *Dark* THEN Time is *Average.*
- IF Batch Size is *Light* AND Drum Speed is *Slow* AND Roast is *Very Dark* THEN Time is *Above Average.*
- IF Batch Size is *Light* AND Drum Speed is *Normal* AND Roast is *Dark* THEN Time is *Above Average*.
- IF Batch Size is *Light* AND Drum Speed is *Normal* AND Roast is *Very Dark* THEN Time is *Long*.
- IF Batch Size is *Light* AND Drum Speed is *Fast* AND Roast is *Dark* OR *Very Dark* THEN Time is *Above Average*.
- IF Batch Size is *Medium* AND Drum Speed is *Slow* AND Roast is *Dark* OR *Very Dark* THEN Time is *Average*.

- IF Batch Size is *Medium* AND Drum Speed is *Normal* AND Roast is *Dark* THEN Time is *Above Average*.
- IF Batch Size is *Medium* AND Drum Speed is *Normal* AND Roast is *Very Dark* THEN Time is *Long*.
- IF Batch Size is *Medium* AND Drum Speed is *Fast* AND Roast is *Dark* THEN Time is *Above Average*.
- IF Batch Size is *Medium* AND Drum Speed is *Fast* AND Roast is *Very Dark* THEN Time is *Long*.
- IF Batch Size is *Heavy* AND Drum Speed is *Slow* AND Roast is *Dark* THEN Time is *Average*.
- IF Batch Size is *Heavy* AND Drum Speed is *Slow* AND Roast is Very *Dark* THEN Time is *Above Average*.
- IF Batch Size is *Heavy* AND Drum Speed is *Normal* AND Roast is *Dark* THEN Time is *Above Average*.
- IF Batch Size is *Heavy* AND Drum Speed is *Normal* AND Roast is *Very Dark* THEN Time is *Long*.
- IF Batch Size is *Heavy* AND Drum Speed is *Fast* AND Roast is *Dark* OR *Very Dark* THEN Time is *Long*.